Polarization Selectivity of Light through Elliptical Nano-hole Arrays in a Metal

R. Gordon, A. G. Brolo, A. McKinnon, A. Rajora, B. Leathem and K. L. Kavanagh

Abstract—**Strong polarization dependence is observed in the optical transmission through nano-hole arrays in metals. It is shown that the ellipticity of the holes leads to this polarization selectivity, and that the orientation of the ellipse leads to enhanced transmission along specific axes of the nano-hole array. Furthermore, the polarization selectivity shows a squared dependence on the aspect ratio of the holes, the origin of which is discussed in terms of coupling into and out of the surface plasmon modes in the metal. The observed results will be useful for tailoring the polarization behavior of metallic nano-photonic elements in several important applications, including surface plasmon enhanced optical sensing and ultra-fast optical switching.**

Index Terms—**Nano-photonics, nano-optics, nano-hole arrays, surface plasmons.**

I. Introduction

Recent works have demonstrated a 10^4 increase in the second harmonic generation from a metal [1], a 40 times increase in the fluorescence of molecules on a metallic surface [2], entanglement preservation through macroscopic plasmon propagation [3], and femtosecond modifications in the transmission through metallic holes [4]. These results are exciting to applications in several fields, including nano-photonic biosensing [5], quantum information processing, and ultra-fast optical switching. The common feature in these phenomena is that they are all consequence of the surface plasmon (SP) mediated enhancement of optical transmission through sub-wavelength holes in metals.

The standard theory for the transmission of light through sub-wavelength apertures predicts that the transmitted intensity decreases as $(d/\lambda)^4$, where d is the hole diameter and λ is the optical wavelength [1]. Extraordinary enhancements, usually greater than three orders of magnitude than that prediction, have been observed when sub-wavelength holes are patterned as a periodic array in a metal film [7]. The normalized transmission efficiency has been shown to exceed unity, so the light is focused through the holes. The enhanced transmission occurs at particular wavelengths that satisfy the Bragg condition, given by the periodicity of the array, using the propagation properties of SP modes [8]. In addition, hole arrays in non-metallic substrates do not show similar enhancements, confirming the role of the SP-modes.

R. Gordon, Dept. of Elec. and Comp. Eng., University of Victoria, P.O. Box 3055, Victoria, Canada, V8W3P6 (e-mail: rgordon@ ece.uvic.ca).

A. G. Brolo, Dept. of Chemistry, University of Victoria, P.O. Box 3065, Victoria, BC, Canada, V8W 3V6. (agbrolo@uvic.ca).

A. Mckinnon, A. Rajora, B. Leathem, and K. L. Kavanagh, Dept. of Physics, Simon Fraser University, 8888 University Dr., Burnaby, BC, Canada, V5A 1S6. (kavanagh@sfu.ca).

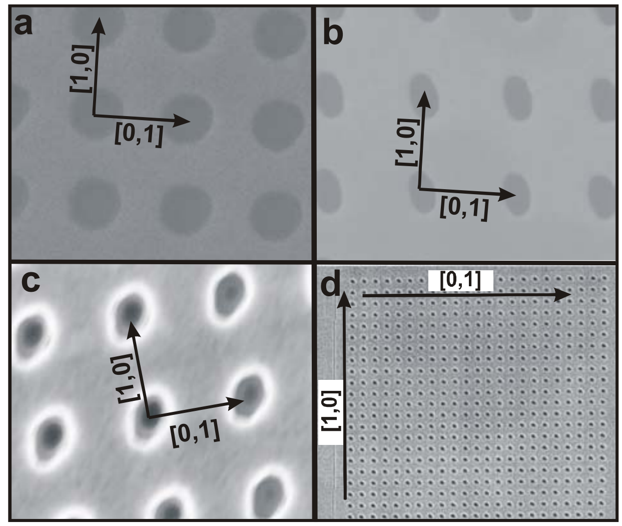

Fig. 1. Scanning electron micrographs of square nano-hole arrays in gold. (a) Nearly circular holes. (b) Elliptical holes, 0.6 aspect ratio and major axis at -12˚ to the [1, 0]. (c) Elliptical holes, 0.6 aspect ratio and major axis at 33˚ to the [1, 0] axis. (d) An expanded view of (c) showing the full 16.1-μm wide array of 529 holes (holes spaced by 704-nm).

The enhanced transmission in arrays has been studied by varying the metal film, the lattice geometry, the hole spacing, the hole diameter, and the film thickness [7], [9], [10]. The effect of the shape and orientation of the holes, however, has not been considered previously. It has even been suggested that, due to the sub-wavelength nature of the hole, the "transmission coefficient depends on hole area, but does not appreciably depend on hole shape" [11]. This is not true when considering the polarization dependence of transmission through anisotropic holes, as is demonstrated here.

In this paper, the light transmission through arrays of sub-wavelength elliptical holes in a gold film is studied by varying the orientation and aspect ratio of the holes. The polarization of the transmitted light is found to be strongly dependent on the orientation and geometry of the holes, and the effect of the aspect ratio is explained in terms of coupling to the SP modes.

II. Experiment

A. Sample preparation and optical characterization

The nano-holes were created using focused Ga-ion beam

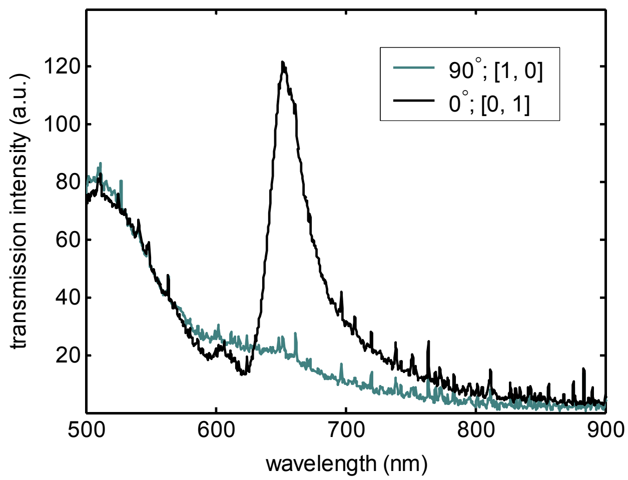

Fig. 2. Transmission spectrum through elliptical nanohole array for two orthogonal linear polarizations, with a 0.3 aspect ratio between the minor and major axes of the ellipse. 90˚ polarization is parallel to the minor axis of the ellipse.

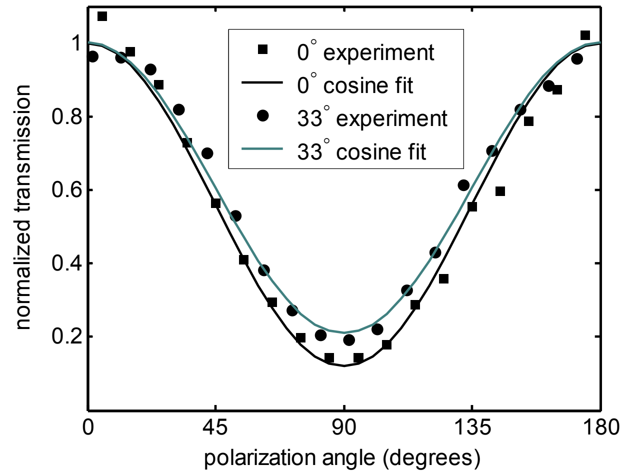

Fig. 3. Polarization dependence of transmission at the [0, 1] resonance peak, normalized to the maximum. Transmission shows cosine dependence when the major axis of the ellipse is oriented both at 0˚ and 33˚ to the [1, 0] axis of the array.

milling (30 keV) of a 100-nm thick gold film on a glass substrate. Several square arrays of 23 × 23 holes with different periodicities were fabricated. The ellipticity of the holes was controlled by using an astigmatic ion beam. The orientation of the major axis of the ellipse was also varied. Figure 1 shows scanning electron micrographs of three samples, demonstrating the ability to create circular and elliptical holes, as well as the ability to control the orientation of the ellipse's major axis relative to the array lattice. The optical transmission spectra of unpolarized light through all the arrays utilized in this work showed the previously reported enhanced resonances, agreeing with the Bragg condition for the SP modes [7].

B. Polarization selectivity with elliptical holes

1) Wavelength selective enhancement

Figure 2 shows the transmission spectrum for two orthogonal linear polarizations of the incident white light. The major axis of the elliptical holes was parallel to the [1, 0] axis of the lattice, the aspect ratio of the ellipse was 0.3, and the spacing between the holes was 500-nm. The peak at 655-nm agreed well with the SP resonance for the gold-glass interface. There was a dramatic reduction in this peak as the polarization was rotated from the [0, 1] direction to the [1, 0] direction (directions shown in Figure 1). The resonant transmission was enhanced when the electric field polarization was perpendicular to the major axis of the elliptical hole.

2) The influence of the elliptical hole orientation

Figure 3 shows the polarization dependence of the transmitted intensity at the resonant wavelength, which is follows a cosine function. The same dependence on the polarization was observed for ellipses oriented parallel and tilted 33^0 to the [1, 0] axis. Even when the ellipse was rotated by 33˚ with respect to the [1, 0] lattice direction, the orientation of the electric field polarization corresponding to a maximum transmission stayed fixed along the [0, 1] direction. The same result was found for different ellipse orientations, and in all cases the polarization maximum followed the symmetry of the lattice. The enhanced polarization was along the lattice direction that was closest to being perpendicular to the major axis of the ellipse.

3) Dependence on aspect ratio

Ellipses with different aspect ratios were tested, each aligned with the major axis along the [1, 0] direction of the lattice, to within 20˚. Figure 4 shows the ratio between the minimum and maximum transmission intensities (i.e., for the two orthogonal polarizations) as a function of the aspect ratio of the holes. The transmission ratio had a squared dependence on the aspect ratio – a log-log fit produced a slope of 2.07. The squared plot is shown with a solid line.

III. Discussion

The strong polarization dependence of the transmission as a function of the ellipse orientation resembles previous observations of transmission through a sub-wavelength slit surrounded by surface corrugations [12]. In that work, it was shown that the enhanced transmission occurs only for the p-polarization, where the electric field is perpendicular to the long axis of the slit. The enhanced transmission for p-polarization was also found in simulations for a 1-D array of grooves in a metal [13]. If we consider an array of elliptical holes with their major axis length equal to the lattice spacing itself, and aligned along the [1, 0] direction, then the holes become a series of parallel grooves. Therefore, in the limiting case we recover a geometry that resembles the 1-D case, and the enhanced polarization is expected to be perpendicular to the major axis of the ellipse, as was observed in Figure 2.

Both the influence of the orientation and the aspect ratio dependence can be understood qualitatively by noting that the direction of the SP mode propagation is parallel to the electric field [8], and by considering that the coupling into and out of the SP modes occurs at the edges of the holes. Since the SP modes propagate parallel to the electric field polarization, the

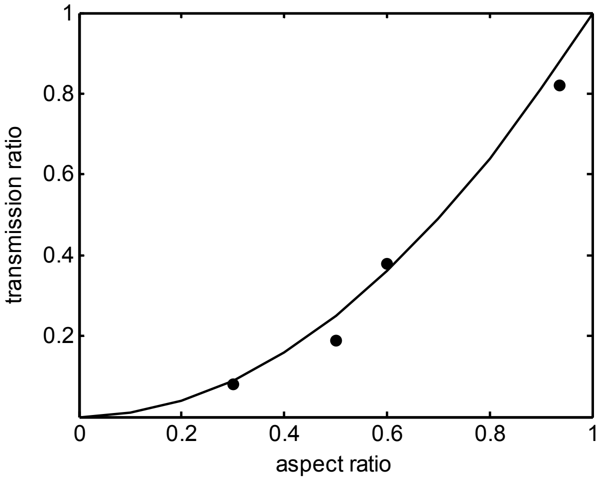

Fig. 4. Experimentally observed ratio between transmitted light polarized along the [1, 0] and [0, 1] axes as a function of the aspect ratio of the holes. Solid line shows the $y = x^2$ curve.

Bragg resonance from the periodic array is aligned with the optical polarization. For example, the [1, 0] Bragg resonance will be excited by a polarization along the [1, 0] direction. Therefore, if the ellipse, by virtue of its orientation, enhances the coupling to the grating parallel to the [1, 0] direction, then the transmission will be enhanced for the polarization along the [1, 0] as well, as was observed in Figure 3.

When the major axis is perpendicular to the polarization of the incident field, the longest edge is parallel to the SP plane wave and the coupling to the SP mode is enhanced. By the same argument, the SP plane waves are scattered most efficiently from the long edges of the holes. As a result, the enhanced Bragg resonance occurs along the lattice vector that is closest to being normal to the major axis of the ellipse.

Finally, we consider the squared dependence on the aspect ratio. The SP enhanced transmission is a resonance phenomenon whereby the SP mode interacts with a periodic lattice grating. The light must couple through the edge of the hole twice to interact with the grating: (1) from free-space into the SP mode, and (2) back out of the SP mode. Therefore, there are two couplings taking place at each surface, and each surface produces a different set of enhanced transmission resonances. Assuming that the coupling efficiency is linearly proportional to the length of the edge of the holes, a square dependence of the enhanced transmission on this length is expected. This agrees with the observed squared dependence shown in Figure 4.

IV. Conclusions

The phenomenon of SP enhanced transmission through an array of holes in a metal is both physically interesting and relevant for a number of device applications. We have studied experimentally the transmission properties of elliptical nano-hole arrays and shown that they provide a mechanism for strong polarization selectivity.

These findings are important for three reasons. First, they provide a means of tailoring the polarization selectivity in nano-photonic devices utilizing the SP mechanism. Second, they quantify the sensitivity of the polarization to the shape of the holes, and thereby define fabrication tolerances for nano-photonic devices where polarization selectivity may not be desirable (e.g., those used in optical networks). Third, these are the first experimental results to explore the polarization dependence and the hole-shape dependence of the SP enhanced transmission, and therefore they will enhance the understanding of the physics of the SP mediated transmission.

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